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14. ABSTRACT
Multi-instrument observations of the ionosphere and plasmaspheric density structure are proposed to address two fundamental areas of magnetospheric-ionospheric coupling physics: (1) To obtain global understanding of the processes governing electrodynamics and plasma production and loss in the low/mid-latitude as a function of local time, season, and magnetic activity, and (2) to investigate globally the main triggering mechanisms that drives equatorial bubbles to higher altitudes; is it interplanetary or ionospheric dynamo electric field or both that triggers bubbles penetrations to higher altitudes?

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FINAL PROGRESS REPORT
AFOSR Young Investigator award FA9550-10-1-0096

TITLE: **Understanding the physics behind ionospheric and plasmaspheric density irregularities by utilizing multi-instrument observations data**

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Proposal Summary: Multi-instrument observations of the ionosphere and plasmaspheric density structure are proposed to address two fundamental areas of magnetospheric-ionospheric coupling physics: (1) To obtain global understanding of the processes governing electrodynamics and plasma production and loss in the low/mid-latitude as a function of local time, season, and magnetic activity, and (2) to investigate globally the main triggering mechanisms that drives equatorial bubbles to higher altitudes; is it interplanetary or ionospheric dynamo electric field or both that triggers bubbles penetrations to higher altitudes? A pair of magnetometers, at the equator and off the equator, at different longitudinal sectors (American, African, and Asian sectors) will be used to estimate the main driving force (**E** × **B** drift) of the equatorial ionosphere electrodynamics. AMBER, MAGDAS, and SAMBA magnetometer stations will be used. The estimated vertical drift will be compared with observation by vector electric field instrument onboard C/NOFS satellite. At the same time the evolution of equatorial ionospheric irregularities will be tracked by the globally growing numbers of ground- and space-based (on Low-Earth-Orbit (LEO) satellites) GPS receivers. The 2D and 3D tomographic reconstruction technique will be applied to ground- and space-based GPS TEC measurements to observe the vertical structure of the ionospheric and plasmaspheric density. In order to observe the frequent bubble penetration into high-altitude during the presence of strong equatorial anomaly, in situ density data from series of DMSP satellite will be utilized simultaneously. Finally, by combining estimated **E** × **B** drift (using magnetometer observation) and vector electric field data from C/NOFS with the simultaneously estimated solar wind electric field (from data recorded by ACE), we will investigate the role of solar wind and ionospheric dynamo electric fields for the formation of equatorial ionospheric irregularities and for the penetration of bubbles to higher altitudes. We can perform this comparison at different longitudinal sectors and understand their longitudinal dependences.

Most Important Progresses Made Since April 2010:

1) For complete understanding of equatorial ionospheric density structure, in coordination with the equatorial vertical E×B drift observation, we performed significant progress in tracking the evolution of the equatorial ionospheric density structures using ground- and space-based GPS TEC measurements as well as the occultation density profiles from COSMIC and CHAMP LEO satellites. We have demonstrated that by reporting very interesting results, showing how the day side counter electrojet significantly affect the ionospheric density distribution and thus communication navigation facilities [*e.g., Yizengaw et al.*, JASTP, 2011].
2) The geomagnetic storm impacts on the mid-latitude ionospheric structure, primarily in the African sector, have less frequently been investigated. Using the recently deployed ground-

based instruments, such as GPS receivers and ionosondes, in the region, we investigated the evolution and generation of the travelling ionospheric disturbances (TIDs) over mid-latitude region in the African sector [*Ngwira et al., JASR*, 2012].

3) The statistical global view of the low-latitudes ionospheric density stimulates further interest in studying the strong longitudinal variability of the ionospheric density structures in the low-to-equatorial latitudes. One of the problems is that we are not completely certain how the electrodynamics and ion-neutral coupling proceeds at low latitudes, in particular, the longitudinal difference in the dynamics of plasma structures in the low-to mid-latitude ionosphere is not yet fully understood. Numerical studies of latent heat release in the troposphere have indicated that the lower atmosphere can indeed introduce a longitudinal dependence and variability of the low-latitude ionosphere during quiet conditions. For the first time, we performed simultaneous observations of the tidally modulated global wind structure, using TIDI observations onboard TIMED satellite, in the E-region and the ionospheric density distribution using ground (global GPS receivers) and space-based (C/NOFS in situ density and GPS TEC on CHAMP) instruments. Our results show that the longitudinally structured zonal wind component could be responsible for the formation of wave number four pattern of the equatorial anomaly [*Yizengaw*, IJG, 2012].
4) In order to see the vertical structure of the ionospheric density distribution, we applied tomographic inversion technique to the ground- and space-based GPS TEC. We, then, simultaneously made a one to one comparison between the altitude distribution of the equatorial anomaly (or fountain effect) and the corresponding vertical E×B drift estimated using a pair of magnetometer technique. To image the vertical structure of the equatorial electrodynamics, we used the LISN GPS network for the South American sector and the sparsely located GPS receivers in east Africa for African sector. We found an impressive correspondence between the development of equatorial anomaly and the strength of vertical E×B drift. We also used Jicamarca ISR density profiles for validation of the density profiles obtained by tomographic reconstruction technique [*Yizengaw et al.*, JGR, 2012].
5) Using the power of tomographic reconstruction technique, we track the density dynamic evolution through time with respect to latitude at a fixed altitude, which can help us in comparing and validating in situ densities observed by LEO satellites. Thus, we made comparison of the in situ densities measured by the Planar Lagmuir Probe (PLP) onboard the C/NOFS satellite with those determined by tomographic inversion at the location of the satellite. In general, the comparison between C/NOFS and tomographically reconstructed densities show excellent agreement, demonstrating that the tomographically reconstructed density can also be used to validate the in situ density values of the newly launched LEO satellites [*Yizengaw et al.*, JGR, 2012].
6) Using observations from multi-instruments, both on the ground and space, we clearly demonstrated that the solar wind driven ULF wave in the Pc5 range can penetrate to equatorial ionosphere and modulate the equatorial electrodynamics and create small scale density perturbation. We used magnetic field observations from space (GOES and C/NOFS) and ground (AMBER, SAMBA, and INTERMAGNET magnetometers) to monitor the penetration of ULF wave at different altitudes. We then use ground-based vertical E×B drift velocity (magnetometer estimated and JULIA 150 km) data to observe how the ULF waves create an oscillating drift velocity, which in turn produce fluctuating density structure. We demonstrated the fluctuating density using GPS TEC. Surprisingly; both of these independently observed data oscillate with nearly identical period (8-10 minutes), which is a

typical period of Pc5 ULF waves. The result has been accepted for publication [*Yizengaw et al.*, JASTP, 2013 *in press*].

7) One important characteristic of longitudinal variability of the ionosphere is the global wavenumber-four signature. Recent investigations have focused mainly in the climatological pattern during daytime and evening sector. For the first time, we investigated the day-to-day variability and the occurrence of the longitudinal structure of the ionospheric density using the quiet time ($Kp \leq 3$) global ground-based GPS TEC. Our day-to-day observation revealed that the wavenumber four patterns occurred in all local time sectors. Our more than two years' worth of data analysis showed that more significant occurrence of wave number four patterns was observed during 1000 - 2400 LT sector, and the maximum occurred during the March-April equinox and June-July solstice. The December-January is the period where the wavenumber-4 structure in average is less dominant than during the rest of the year [*Pacheco and Yizengaw*, 2013 *in press*].
8) Space-based instruments reputedly show significant longitudinal differences in the formation of equatorial bubbles, scintillation, and the potential driving mechanisms of vertical $\mathbf{E}\times\mathbf{B}$ drifts. For example, satellite observations have shown very unique equatorial ionospheric density structures in the African region. The African region is the longitude sector where the occurrence of large scale bubble activity (zonal width, depletion level, and spacing) peaks significantly compared to other longitudinal sectors. One of the possible driving mechanisms that govern the equatorial electrodynamics is the vertical $\mathbf{E}\times\mathbf{B}$ drift, which strongly affects the structure and dynamics of the ionosphere in the low/mid-latitude region. Until recently, the uneven distribution of ground-based instruments in the equatorial regions hindered our ability to obtain the temporal and longitudinal variability of the dynamics and structure of the equatorial ionosphere, largely due to the lack of observing instrumentation in Africa. Ionospheric density structure in the African sector has been only estimated by model interpolation over vast geographic areas. However, during the past couple of years, a number of small instruments have been deployed in Africa. Recently, we successfully developed a routine technique that can detect the equatorial bubbles from the ground-based GPS TEC observations. Therefore, using the available GPS receivers that are deployed in the equatorial regions, we successfully observed, for the first time, the longitudinal variability of the equatorial bubbles from the ground. We also performed similar observation from space-based instruments, C/NOFS PLP density, and compared it with the longitudinal differences in bubbles and scintillation observation performed from the ground. Finally, using the magnetometer data, for the dayside drift estimation, and the IVM and VEFI drifts, for the evening and nightside, we addressed the impact of the vertical drift velocity for the formation of longitudinally variable equatorial bubbles and scintillation activities. The result of this research has been presented at the 2013 C/NOFS meeting in Albuquerque, and will be submitted for publication very soon [*Yizengaw et al.*, GRL, 2013a].
9) Using five pairs of magnetometers located in the African (two pairs: at the East and West Africa) and American (three pairs), we routinely estimate the equatorial electrojet (EEJ), and thus the vertical E×B drift difference at different longitudinal sectors. The longitudinal variation of equatorial electrojet and thus the vertical E×B drift has been compared for the first time using ground-based instrumentation. This was possible due to the successful deployment and operation of AMBER magnetometer network in the equatorial region of Africa, a region that was devoid of ground-based instrumentation. We also made a routine comparison between the magnetometer estimated vertical E×B drift with other independent

drift observation, such as JULIA 150 km drift velocity and drift measurements with VEFI and IVM instruments on board C/NOFS satellite. We also use ACE and/or WIND data to estimate the interplanetary electric field and monitor its penetration to the ionosphere by comparing it with the ground-based E×B drift observation along with IMF BZ orientations. Therefore, with the proposed (pending AFOSR proposal) pairs of magnetometers, which are proposed to be deployed at the equatorial region of different longitudinal sectors, we will be able to estimate the dayside vertical drift velocities at different longitudinal sectors. Obtaining the global drift velocity distribution will allow us to understand the global electrodynamics that controls the equatorial density irregularities which are critical for our navigation communication systems.

10) It has been known since many decades that lunar tide has an influence on the strength of the equatorial electrojet (EEJ) and thus on the vertical ExB drift. The EEJ intensity and thus the vertical drift velocity are enhanced around noon, shortly after new and full moon. The lunar tide effect can be identified as it causes a semi-diurnal wave that continues through all local times within one lunar month. However, except the climatology space-based LEO satellite observational studies, no comprehensive global study, especially the longitudinal dependence of lunar tide influence on EEJ and vertical drift velocity, have been performed. Using our pairs of magnetometers in the American and African sectors, we investigate the longitudinal dependence of the lunar tide effect for difference lunar months. Similarly, we also investigated the impact of the longitudinal lunar tides difference on the global TEC distributions. This combined, lunar tide impacts on EEJ and GPS TEC, investigation result will be soon submitted for publication [*Yizengaw et al.*, GRL, 2013b]. At the time of this report, this work is on progress.

11) Ionospheric empirical model, such as NeQuick 2, depends on F2 peak and topside ionosphere parameters that can be estimated using ground-based ionosonde and topside sounders. However, the uneven distribution of ground-based instruments and very limited topside sounders have been the barriers for the development of a reliable empirical model that can specify the ionosphere, especially in the region where there are very few ground-based instruments available. For the first time, we investigated the performance of one of the empirical model, NeQuick-2, in estimating the topside ionospheric density structure in the East African region. We performed the test without assisting the model and by assisting the model with the GPS TEC data obtained from the nearby ground-based GPS receiver, which means by driving the model with different ionization parameter, deviating from the actual F10.7 parameter, until the model produce the TEC that best fits the GPS TEC measurements. We then use the ionization parameter (effective ionization parameter) and run the model at nearby different locations and produce the spatial distribution of the density profiles of the ionosphere in the East African region. Finally, the performances of model output, both before and after data ingestion, in estimating the topside density profiles has been carried out by comparing it with the C/NOFS PLP in-situ density observations at the corresponding locations. We found that the performance of the model, after data ingestion, reproduces the topside ionosphere better than that of before adaptation [*Nigussie et al., JASTP*, 2013b].

12) Ultra Low Frequency (ULF) waves are dynamic changes in the magnetosphere, primarily driven by the solar wind, and have provided an excellent diagnostic of the magnetospheric state for over 100 yrs now. Using a complete north to south chain of conjugate ground-based magnetometers, we investigated the asymmetries in the power of ULF waves and the role of the ionosphere in such observed asymmetries; and demonstrated that the northern hemisphere

consistently shows higher ULF wave power. Similarly, the GPS TEC observation at the northern hemisphere always shows significantly higher TEC values compared to the GPS TEC observed by the conjugate GPS receiver in the southern hemisphere [*Sterner et al., JGR*, 2013].

Publications

Yizengaw, E., E. E. Pacheco, and C. E. Valladares (2013b), Longitudinal and Seasonal Variation of Lunar tide strength, *to be submitted to Geophys. Res. Lett.*

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The following published abstracts and invited talks are some of the accomplishment that we performed since April 2010.

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